Pbar Momentum Mining in the Recycler

Simulation and Beam Studies

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RR Note

Abstract:

Here we propose a scheme to extract 36 anti-proton bunches at ≤ 1.5 eVs with equal intensities from a Recycler stack. The scheme is illustrated with ESME simulations and with beam experiments using protons. The results of beam experiments are very promising. The method presented here is first of its kind.

I Introduction

The Fermilab has planned to use the Recycler [1, 2] as the main antiproton storage ring for future proton-antiproton collider operation. This will be achieved in two phases. In the first phase, about 200E10 antiprotons will be stacked and cooled using the stochastic cooling to $\approx$ 100 eVs longitudinally and $\approx$ 10π-mm-mr transversely [3]. In the second phase the anti-proton stack size is expected to be in excess of 600E10 and the electron cooling will be added. The projected longitudinal emittance is less than 54 eVs. In both the cases the stored cooled beam will be transferred to the Tevatron for proton-antiproton collider operation. The beam stacking in the Recycler and transfer to the Tevatron *via* the Main Injector comprises of complicated sets of RF manipulations [4] and it is highly essential to maintain the emittance of the beam through out.

The antiproton injection to the Tevatron takes place in nine transfers of groups of four 2.5MHz bunches each, with a total of thirty six bunches. For the best performance of the collider, it is desired that the longitudinal emittance of individual bunch from the Recycler to be $\leq$1.5 eVs and the same intensity for all bunches. To achieve this goal here we present a very novel method of RF manipulation "momentum mining", which allows one to capture selectively only the high density low longitudinal emittance beam for collider use and trap the unused high momentum antiprotons for future use. This method thus eliminates wastage of high momentum antiprotons in the entire process of beam transfer to the Tevatron.

In section II we present theoretical simulations using multi-particle beam-dynamics code ESME [5]. Results of the first beam experiment are presented in section III.

II Theoretical Simulations of Unstacking of Cooled Antiprotons

Beam dynamics simulations are carried out for two unstacking scenarios. In the first scenario, we assume that the total stack-size of the antiproton is ≤54 eVs. Our goal here is to divide the stack into nine equal parts and extract each part in succession to the Main Injector after further division of each part into four 2.5MHz bunches. This gives us total of 36-bunches with longitudinal emittance ≤1.5 eVs each. In the second scenario, we assume that the longitudinal emittance of the anti-proton stack is in excess of 54 eVs. This method allows us to extract 36 bunches with longitudinal emittance ≤1.5 eVs bunches to the Main Injector and trap the unused high momentum particles in a separate bucket.

All RF manipulations in the Recycler are performed using rectangular barrier buckets. The maximum available RF voltage is 2kV. Table-I lists the Recycler machine and beam parameters used in the simulations.

Table–I: The Recycler machine parameters.

Parameters	**Values**
Mean Radius of the Recycler	528.3019 meters
Nominal γ_T	19.9678
Beam Energy E_0, Momentum	8.938 GeV, 8.889 GeV/c
Maximum RF voltage for the barrier buckets	2kV
Slip Factor η	-0.0085
Revolution Period T_0 and frequency f_0	11.13 μsec, 89.84 kHz
The extent of the cooled bucket and stack size	≈ 1.6 μsec, ≤54 eVs@620E10 with e- cooling[i] ≈100 eVs@200E10 with stochastic cooling
Anti-proton bunch properties at extraction	≤1.5 eVs /2.5 MHz bunch

[i] The Run II upgrades plan [1] states that the bunch intensity at collision point as 130E9/bunch. By taking into account of the acceleration and transfer efficiencies, an initial anti-proton bunch intensity is estimated to be about 170E9/bunch (David McGinnis, Private communications, September, 2003).

i. <u>AntiprotonSstack ≤54 eVs</u>:

At the start of unstacking process, the length of the cold antiproton stack distribution is approximately 1/7 of the Recycler size, *i.e.,* about 1.6 μsec long. Such a stack is stretched to about 8.5 μsec (450 buckets of 53MHz type) adiabatically in about 50 sec. Figure 1A shows the phase-space distribution of the stretched distributions of the antiprotons. The dotted lines show the barrier bucket boundary. The azimuthal

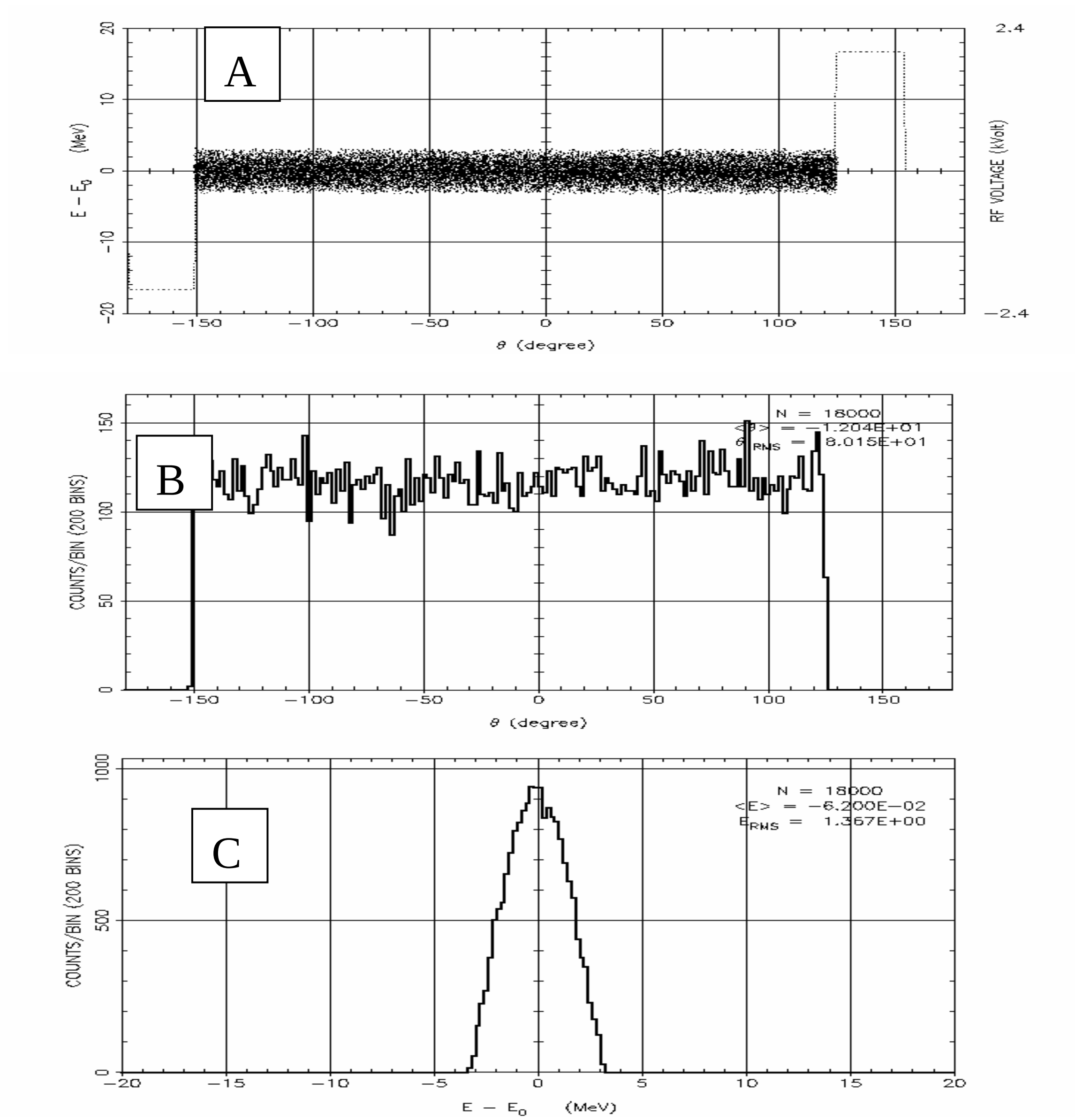

Figure 1: ESME simulations for (A) (ΔE,Δθ) distribution of 54 eVs antiprotons in the Recycler stretched to about 8.5 μsec (450 53MHz buckets) (B) θ- projection for the distribution shown in "A", (C) The predicted energy spectrum of the beam particles.

projection and the energy spectrum of the antiproton distribution are shown in figure 1B and 1C. The predicted energy spread and rms spread are about 3.2 MeV and 1.37 MeV, respectively. After the stretched beam distribution reaches equilibrium, nine equally spaced back-to-back barrier buckets with 950 nsec wide each are developed adiabatically to make nine bunches with equal intensity. The emittance of each bunch will be ≤6 eVs (like the first eight bunches in figure 2A). The amount of final stretch (see figure 1A) depends on the choice of the size of barrier buckets which are used to divide the stack into nine equal parts. The choice of minimum area of each bucket should be larger than $1/9^{th}$ of the total beam area of the stretched distribution to get nine bunches. It should be noted that the particles in these types of back-to-back barrier buckets have very large synchrotron frequency and are less prone to external disturbances.

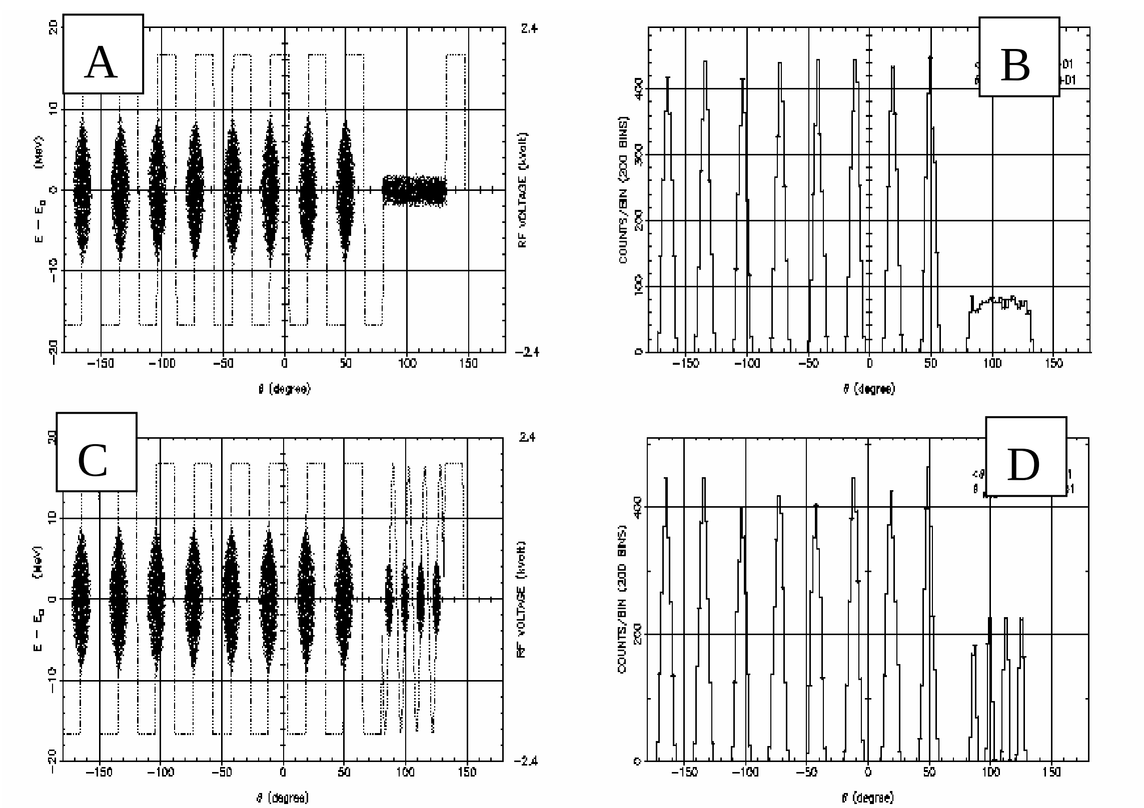

Figure 2: Simulated phase space distribution of the beam particles at different stages of unstacking (A) nine 6 eVs bunches with the ninth bunch in the extraction region and after growing it by 84 buckets (B) θ projection of "A", (C) after growing four 2.5MHz bunches for injection to the MI for collider shots (D) θ projection of "C".

Once the nine bunches are formed, the barrier bucket used for confining the initial beam distribution shown in figure 1A (two pulses of 2 kV height and about 0.906 μsec wide each) are turned off. This helps us to provide extra azimuthal space in the Recycle for further RF manipulations for beam extraction. At this stage, the last bunch will be moved slowly to extraction region and is stretched by 1.6 μsec to develop four 2.5MHz bucket isoadiabatically as shown in Fig. 2. The total azimuthal length used for the beam extraction is about 3.1 μsec which includes, the kicker rise time and fall time. By repeated application of this method we can divide a 54 eVs distribution into thirty-six equal parts of 1.5 eVs bunches in about 402 sec.

Table II. The time required for various RF manipulations for unstacking the distribution in equal nine parts and ready for transfer to the Tevatron.

Description of RF Manipulations	**Time in sec**
Adiabatic slicing of the original beam distribution	
Growing 1.6μsec wide distribution to 8.5μsec wide distribution	50
Slicing the distribution into nine equal parts	10
Total time	**60**
Preparation for final antiproton transfer to the Tevatron	
Cogging the last distribution to extraction region	10
Stretching the last distribution by 1.6μsec	10
Growing four 2.5MHz bunches adiabatically	8
Cogging rest of the eight bunches in the barrier buckets to as close to the extraction region as possible	10
Total time (this will be repeated nine times per Tevatron store)	**38**

The time required for various stages of the RF manipulation for this scenario are listed in the Table II. The time required for preparing nine equal parts from the initial cooled beam is about 60 sec. This RF manipulation will be performed once per Tevatron store. The subsequent steps of preparing 2.5MHz bunch need about 38 sec and will be repeated nine times.

***ii. <u>Antiproton Stack with Longitudinal Emittance >54 eVs</u>*:**

Extracting 36 bunches of antiprotons at 1.5 eVs each from a stack with longitudinal emittance larger than 54 eVs is a little bit more complicated. Here we propose a method which extracts only the low emittance, high density beam to the collider. In this case, the cooled beam distribution is stretched to the maximum available length azimuthally while allowing gaps for beam extraction. The optimum length for this distribution is found to be about 8.68 μsec with an extraction gap of 2.45 μsec reserved for later use.

Figures 3-5 display the simulated anti-proton distributions for all beam RF manipulations corresponding to the initial longitudinal emittance of 100 eVs. After stretching the distribution (see figure 3A), nine 6 eVs buckets are opened as shown in Figure 3B. The bucket pulse width is selected to be 340 nsec and the required pulse height for the barrier bucket at this stage is about 0.7 kV. The nine barrier buckets will occupy about 6.14 μsec of the Recycler circumference. Now a bigger barrier bucket is opened slowly with total bucket area of 46 eVs (pulse height =0.9 kV and width =1.27 μsec). This bucket is intended to trap the high momentum particles which can not be captured by the other nine barriers buckets. The simulations results show that the phase space distribution has two regions one with low momentum particles from the original stretched distribution and a second ring made up of high momentum particles which are outside of the nine barrier bucket separatrices as shown in figure 3C. The time required for this operation is about 5 sec.

After allowing sufficient time for high momentum particles to drift and become trapped in the big bucket, the barrier bucket heights have been increased simultaneously to 2 kV. The rest of the beam extraction process shown in figures 4C and 5A-5C are almost identical to the 54 eVs case explained earlier. These sequences of RF manipulations guarantee the selection of low momentum particles for collider operation and high momentum particles to be retained in the Recycler for later cooling and use.

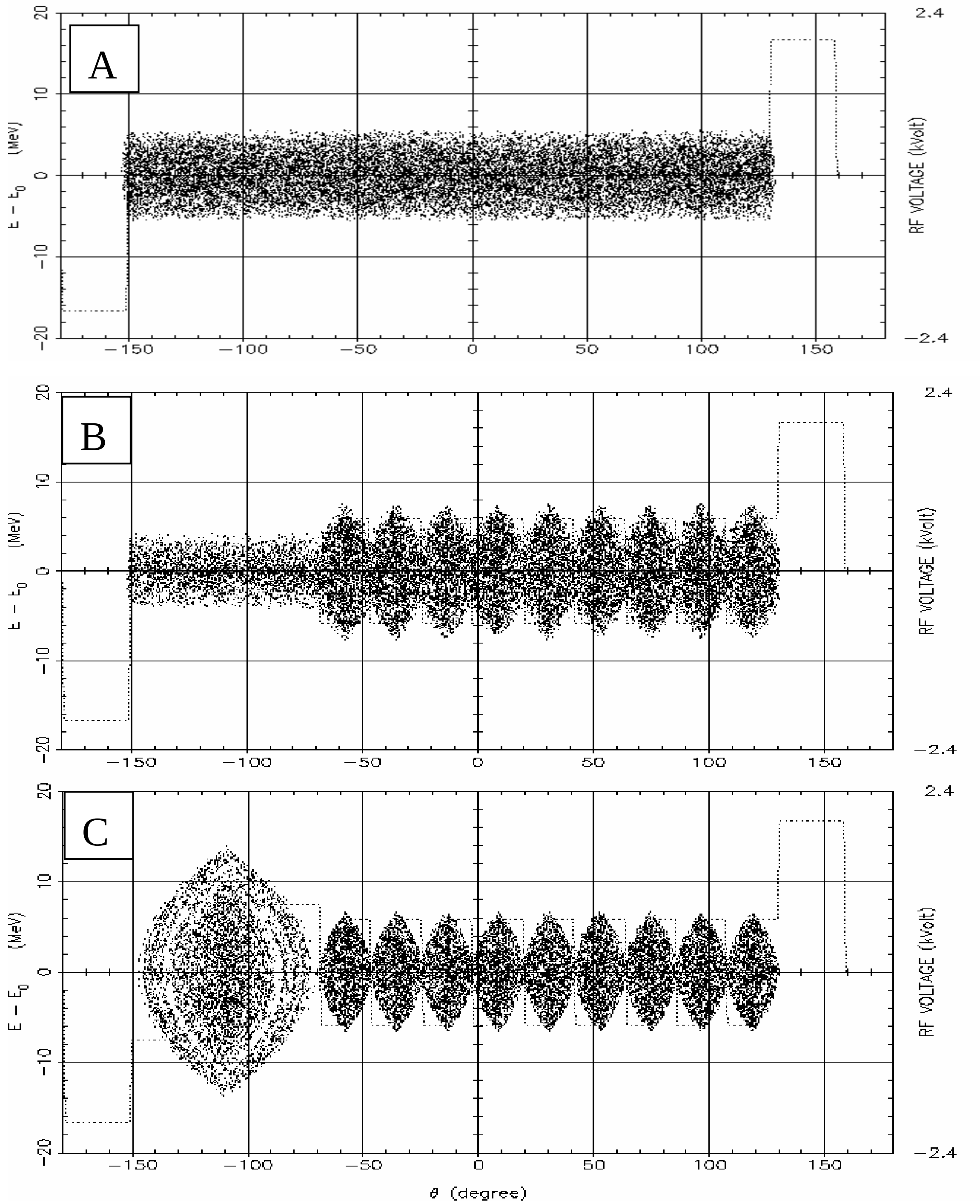

Figure 3: The simulated distribution of 100 eVs anti-protons (A) stretched to 8.68 μsec. (B) adiabatic capture in nine 6 eVs bunches, (C) adiabatic capture of high momentum particles in a bigger barrier bucket. In this case the ten buckets are only partially opened. For other details see caption for figure 1.

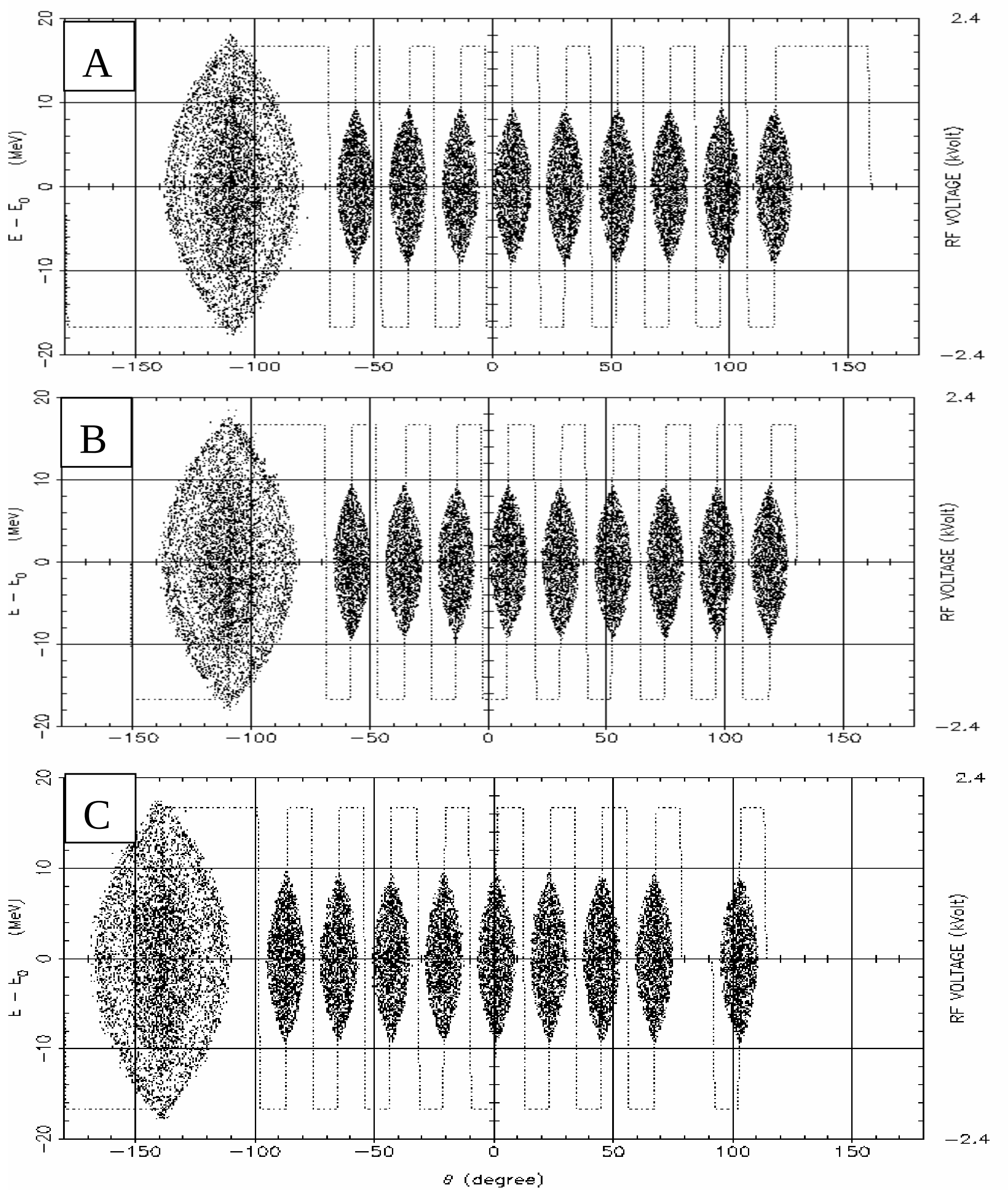

Figure 4: Continuation of RF manipulation from figure 3. (A) After adiabatically increase of barrier bucket pulse heights, (B) after removing initial barriers, (C) after moving last 6 eVs bunch to extraction region. For other details see caption for figure 1.

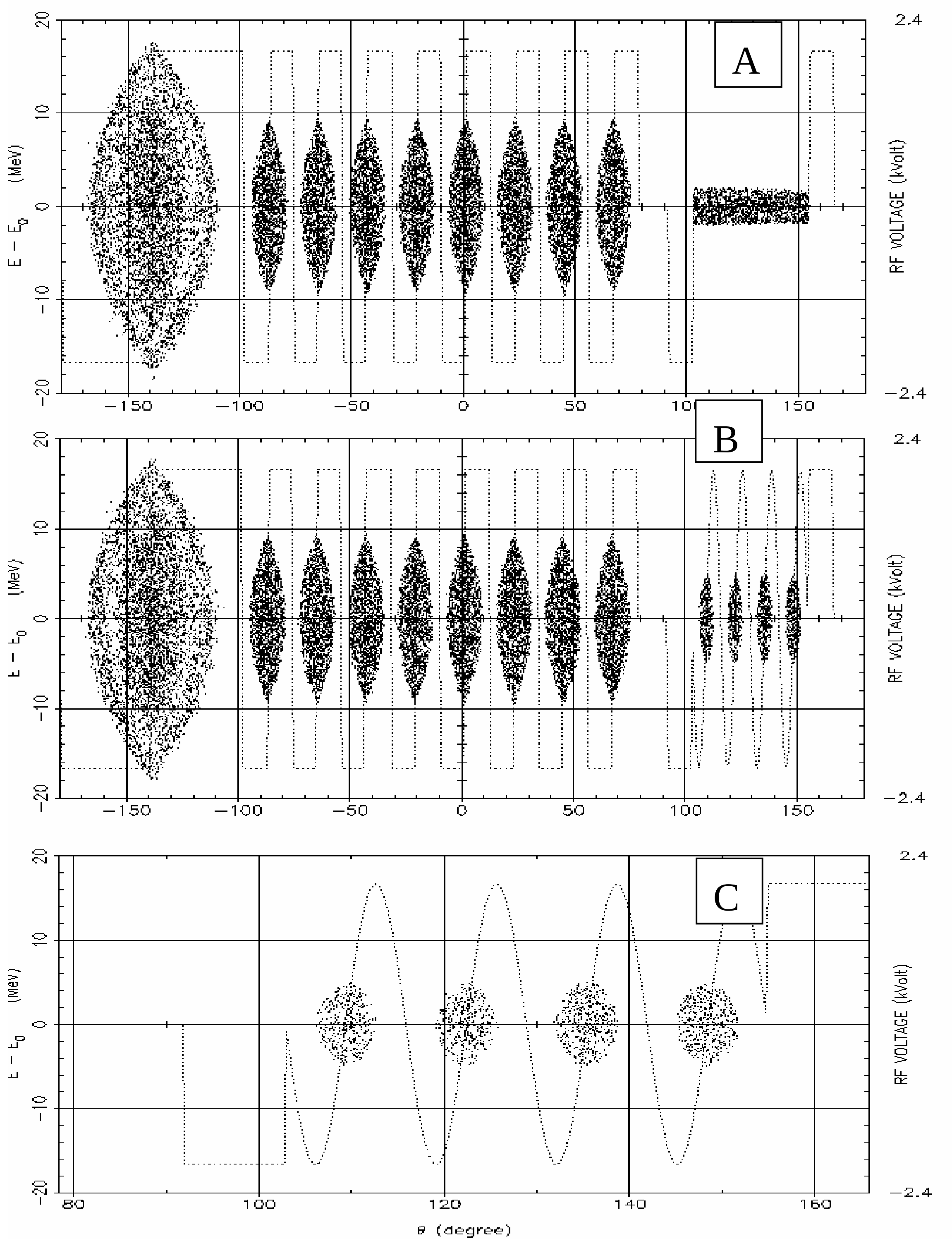

Figure 5: (A) Grow the transfer bucket. (B) producing the 2.5MHz bunches. (C) four 2.5MHz bunches of 1.5 eVs each in the transfer region. For other details see caption for figure 1.

Table III. The time interval for RF manipulations for unstacking 1.5 eVs bunches from 100 eVs anti-proton stack.

Description of RF Manipulations	**Time in sec**
Adiabatic slicing of the original beam distribution	
Stretching 1.6μsec wide distribution to 8.68μsec wide distribution	60
Slicing the distribution into nine equal parts	10
Trap high momentum particles	5
Increase barrier RF voltages to 2 kV	4
Total time	**79**
Preparation for final antiproton transfer to the Tevatron	
Cogging the last distribution to extraction region	10
Stretching the last distribution by 1.6μsec	10
Growing four 2.5MHz bunches adiabatically	8
Cogging rest of the eight bunches	10
Total time (this will be repeated nine times per Tevatron store)	**38**

Table III lists the time taken for each of the processes described here. Care was taken to perform isoadiabatically every stage of the RF manipulation. The time required for the momentum mining is about 80 sec. The rest of the RF manipulations take same amount of time as that of 54 eVs case.

These simulations can be extended to any final desired 2.5 MHz bunch emittance. For example, if we want to inject 2.5 MHz bunches of 1 eVs each to the Main Injector, then one need to open nine barrier buckets of 4 eVs each and trap the high momentum particles in a bucket using similar RF manipulations shown in figure 3. The rest of the RF manipulations will be similar to the case explained earlier.

III Beam Studies (Preliminary)

A series of experiment has been carried out using proton in the Recycler as a proof of the principles developed in Section II. The existing Recycler RF control system cannot allow performing an experiment in complete accordance with the simulation. The present LLRF [6] generates an RF wave that is sum of eight arbitrary wave forms that are two hundred fifty six 53 MHz buckets long. To reproduce the results of simulations one needs wave forms that are 588 buckets long. Therefore, we performed a test of the principle of the momentum mining using only four bunches.

A 40 eVs proton bunch was formed in a rectangular barrier bucket with pulse width of about 0.905 μsec and with a pulse gap of 1.6 μsec. The goal of the experiment was to capture low momentum protons in four 6 eVs bunches and capture the reminder in a bigger bucket. Finally, the last 6 eVs bunch was sliced into four bunches at 1.5 eVs each with equal intensity

The initial 1.6 μsec long distribution was stretched by about 3.1 μsec in about 40 sec using slow cog rate given to by LLRF controls [6]. Subsequently, four barrier buckets of bucket area of 6 eVs were opened with a pulse height of about 0.7 kV by linearly increasing the pulse height in about 5 sec. After about 3 sec a 1.9 μsec wide barrier bucket of pulse height 1 kV was developed to trap the rest of the beam. The area of this bucket was chosen to be about 30 eVs. Once all the protons were trapped in the barrier buckets (in approximately 8 sec) the pulse heights for all barrier buckets were raised to 2kV in about 2 sec. We find that the average longitudinal emittance of the four bunches of interest was about 6 eVs each. Finally, the right most bunch was pulled to extraction region and stretched further adiabatically in about 20 sec and four 2.5MHz bunches were produced. The wall current monitor data for the final beam particle distributions and the RF wave form are shown in figures 6 and 7. The results of measured longitudinal emittance are listed in Table IV.

We find that there is emittance growth at the level of 20% after the RF manipulations. The majority of the growth occurs during the trapping of the high momentum particles. We ended up a longitudinal emittance of 22.8 eVs in the left most bucket in figure 6.

According our simulations we expect beam intensity to be equal for all three bunches and sum of all four 2.5MHz bunches. The beam studies showed that they are differing by about 15%. Similarly, the final 2.5MHz bunch intensities also differ at the level of 40%. This difference arises due to base-line distortion between barrier pulses. During stretching the barrier bucket from 1.6 μsec to 4.7 μsec we have seen a small amount of harmonic components like h=1 and h=2 at the level of few volts. These low harmonic components affect the beam particle distribution and make them cluster more in some parts of the barrier bucket. As a result, when the 6 eVs bucket are opened, some buckets tend to have more particles. Similar phenomenon is responsible for the un-even distribution of particles in the 2.5MHz bunches. These problems can be cured by applying a proper compensation to correct the baseline. This work is in progress.

Table IV: The results of emittance measurements for the data shown in figure 6.

Description	**Bunch No.**	**Bunch Length (nsec)**	**Longitudinal Emittance [A] (eVs)**
Beam before Unstacking Left side penetration Right side penetration Between barrier pulses		 250 300 1609	40
Beam After momentum mining			
Barrier Buckets			
Barrier bucket with high momentum	1	1160	22.8
Low Momentum	2	480	6.1
	3	490	6.3
	4	500	6.4
Beam in transfer Region			
2.5MHz Bunches	5	195	1.4
	6	210	1.6
	7	210	1.6
	8	230	1.9
		Total	**48.1**

[A] Error in the measurement is ≈20% for the beam in stretched distribution and ≈10% for the beam in back-to-back barrier buckets and 2.5MHz buckets.

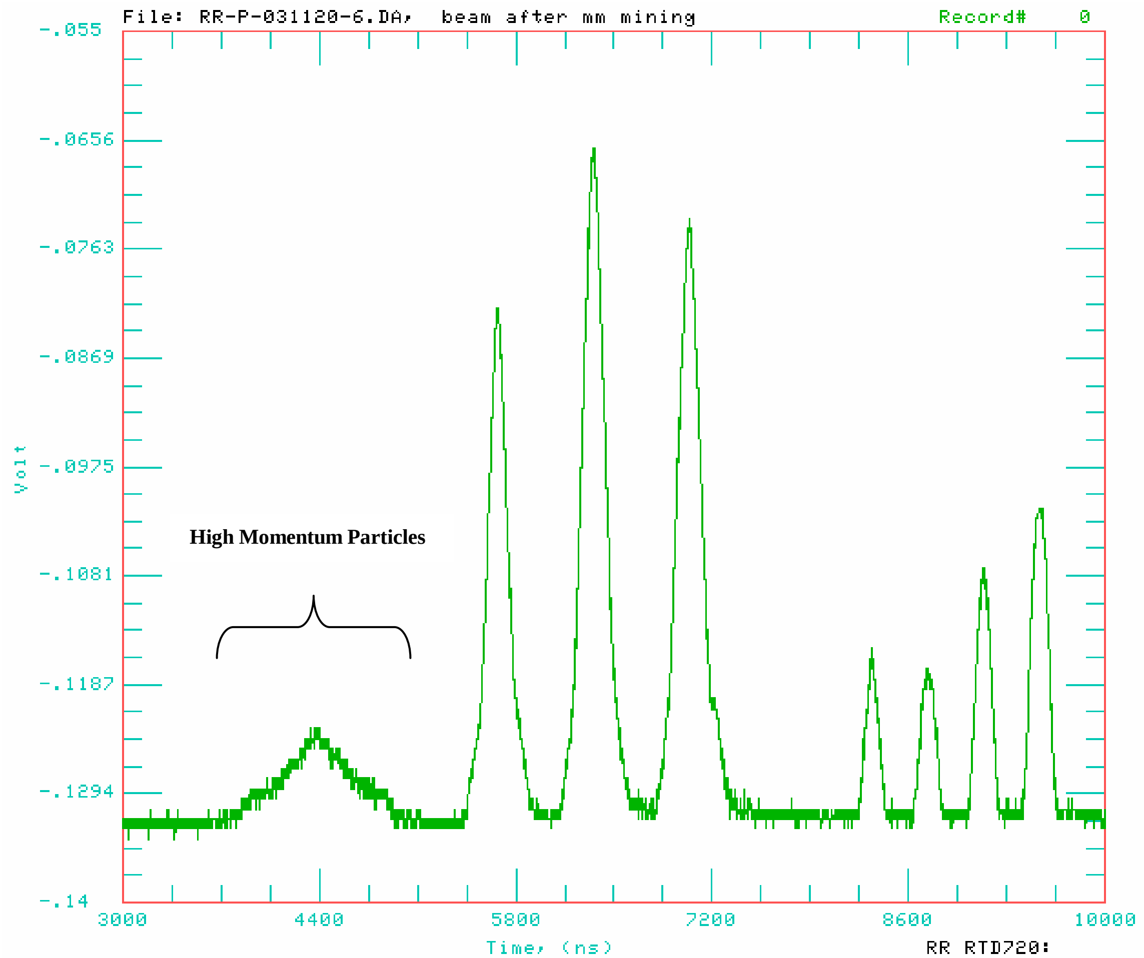

Figure 6: Wall Current Monitor data for momentum mining on the Recycle beam. The first bunch from the left is formed out of high momentum particles of the original stack. The next three bunches have an average of about 6.2 eVs (with in 5% all of them have same longitudinal emittance) and are formed using barrier buckets of 680 nsec (2x340 nsec) and 2kV each. The last four bunches are formed using a 2.5 MHz sinusoidal wave amplitude of 2kV.

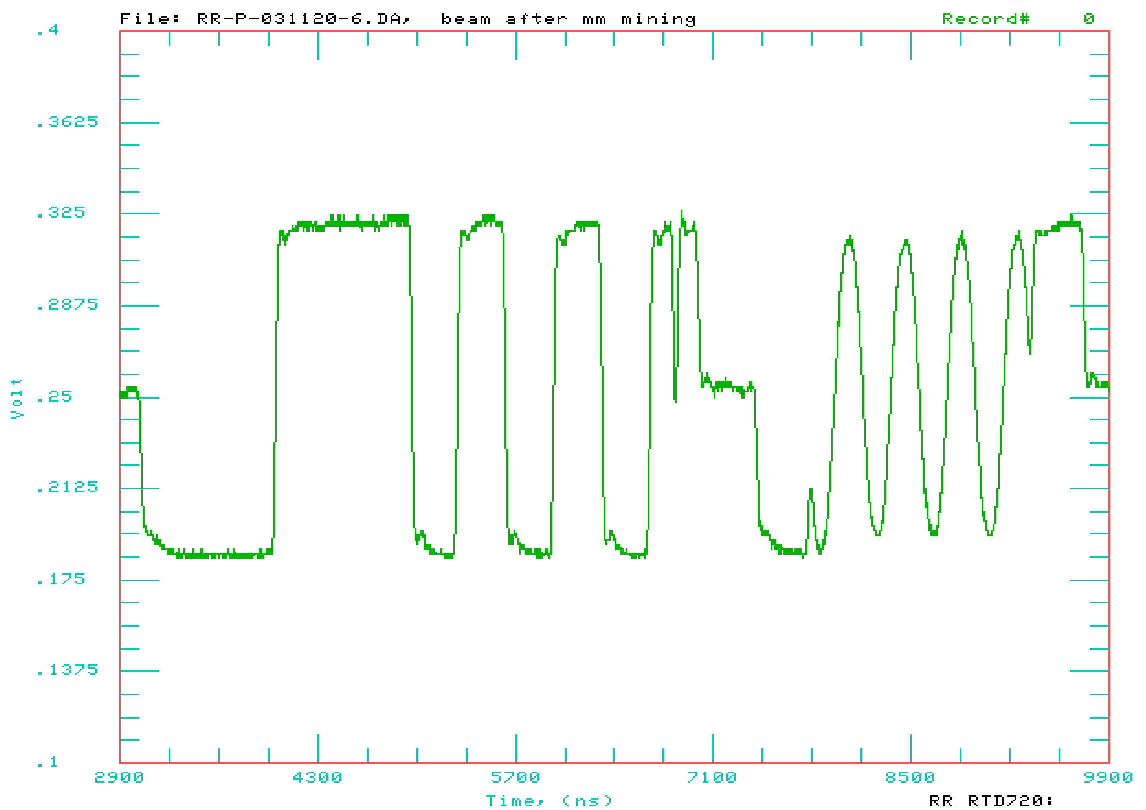

Figure 7: The final barrier voltage waveform used to get the beam particle distributions shown in figure 6. The amplitude for wave is -2kV to +2kV. The vertical scale in the figure is in some relative units. The horizontal scale is in nsec.

IV Summary

I have proposed a novel method of extracting equal longitudinal emittance beam out of a Recycler anti-proton stack. First I illustrated the scheme using multi-particle beam dynamics simulations for two cases. I have also carried out beam experiments in the Recycler using protons. The results are very promising. I was able to do momentum mining and capture the low momentum particles in four 6 eVs barrier bunches. The high momentum particles have been captured in a separate barrier bucket for future use. Further, I demonstrated the method of slicing each 6 eVs bunch into four 2.5MHz of about 1.5 eVs each.

During momentum mining for the case with longitudinal ≤ 54 eVs, we have trapped some low momentum particles along with the high momentum particles (e.g., in the left most bucket in figure 3C). By extending the method proposed here one can select only highly cooled particles for collider use and separate all high momentum particles. Presently we are working on this improvement.

The author would like to thank John Marriner for many useful discussions. I also thank Brain Chase for his help in LLRF issues and Jim MacLachlan for his help in issues related to simulations.

References:

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3. "FY 2004 Recycler Operational Scenario, Responsibilities and Parameter Measurements," Prepared by Recycler Group, last modification by Sergei Nagaitsev Nov. 3, 2003.
4. "RF Manipulations in the Recycler Ring for Stacking and Unstacking of Pbars: Simulations and Beam Studies," Chandra Bhat, (document under preparation); "Barrier Buckets in the Fermilab Recycler Ring," C.M. Bhat, Proc. of "High Intensity and High Brightness Hadron Beam" 20th ICFA Advance Beam Dynamics Workshop on High Intensity and High Brightness Hadron Beams, APS AIP conference proceedings 642 edited by W. Chou et al, 2002; " Simulations of Stacking and Unstacking in the Recycler Ring," C.M. Bhat, PAC2003, , Portland, Oregon., http://warrior.lbl.gov:7778/PAC_PUBLIC/search.html
5. Recent development in "ESME- longitudinal beam-dynamics simulation code," J. MacLachlan, (improvements to incorporate barrier bucket rf manipulations, private communications 1996), http://www-ap.fnal.gov/ESME/.
6. Recycler LLRF Control System, Brian Chase and Keith Meisner (private communications)

Appendix I (January 24, 2004)

Over the last one month I have made significant progress in momentum mining of the beam in the Recycler Ring using proton beam. In my original proposal, a great deal of simulations was carried out in separating the low momentum particles from the high momentum particles and to divide the low momentum particles into nine equal parts. The emphasis was given to create 36 bunches each with 1.5eVs and with equal intensity (see figures 3-5). The first beam experiments were carried out with original LLRF wave-form configurations and maintaining their functionality. Therefore I was able to create only up to four low-momentum bunches and capture all high momentum particles in one barrier bucket (see figures 6 and 7). Here I discuss recent improvements in momentum mining techniques and results from beam experiments. Before the nine bunches are created I tried to move all particles below certain energy spread to a particular region of the stretched barrier bucket by creating an additional potential well. A schematic view of the process is shown in figure AI-1. Nine equal area barrier buckets are opened in the region with particles with low momentum. The rest of the steps followed are similar to the simulations shown in figures 3-5.

The results from a beam experiments are shown in figures A2-A5. These are the order of occurrences. In each of the figures the top trace is the rf wave and the bottom trace is data from wall current monitor representing the longitudinal beam profiles. The figure A2 shows initial beam distribution (top) and after the beam is stretched by about 9 μsec. The stages of momentum mining are shown in figure A3. The final stages before extraction of the bunches are shown in figures A4 and A5. The large barrier bucket in figures A4 and A5 to the left is for capturing the large momentum particles. Its area is about 70eVs. The rest of the buckets are about 10.2eVs each with 6 eVs beam bunches as shown in the lower trace. The figure A5 four 2.5MHz bunches just before transfer to the MI.

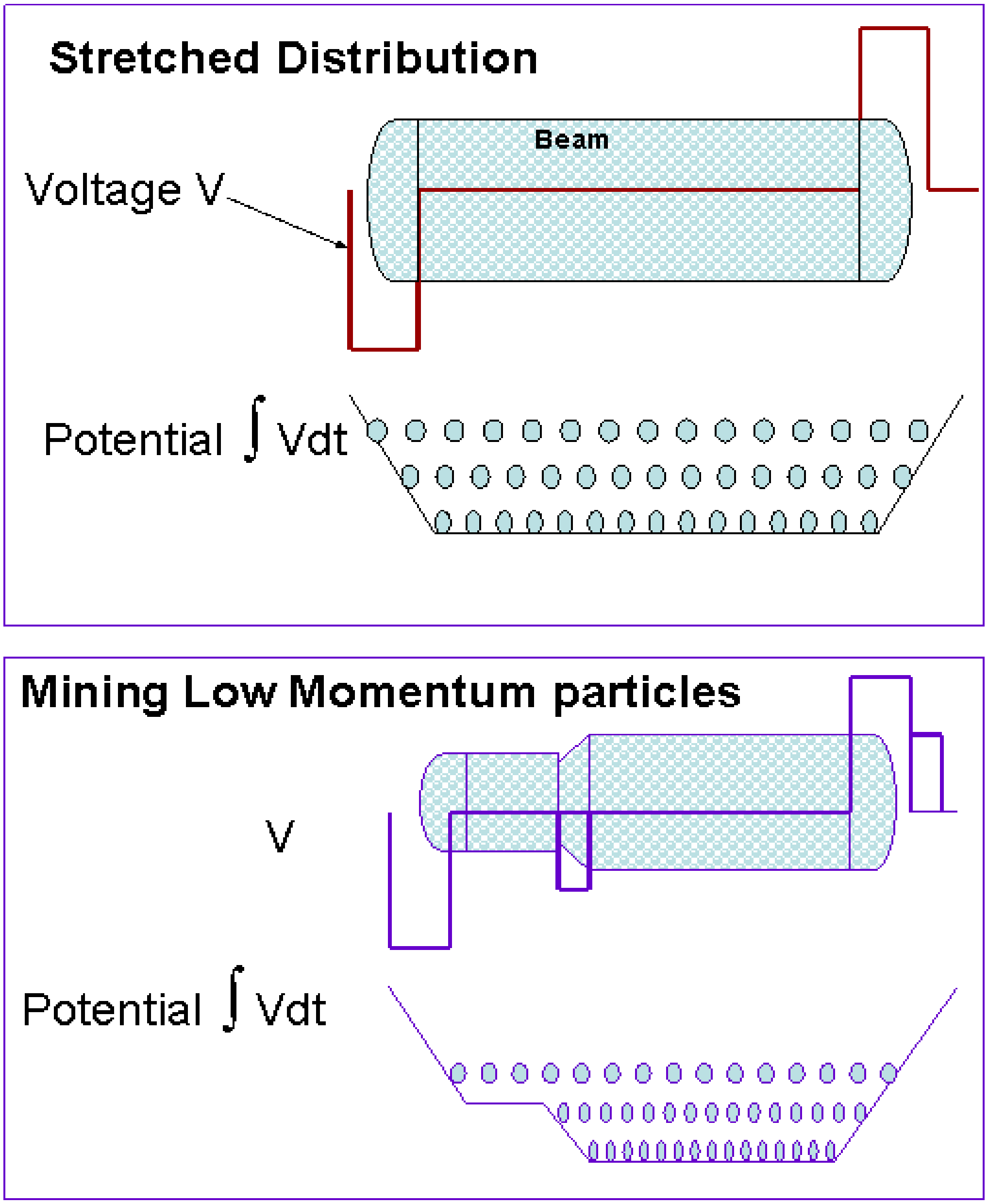

Figure AI-1: Schematic view of stretched distribution and its potential diagram (top) and creation of additional valley to collect the low momentum particles where in nine equal emittance bunches will be developed later.

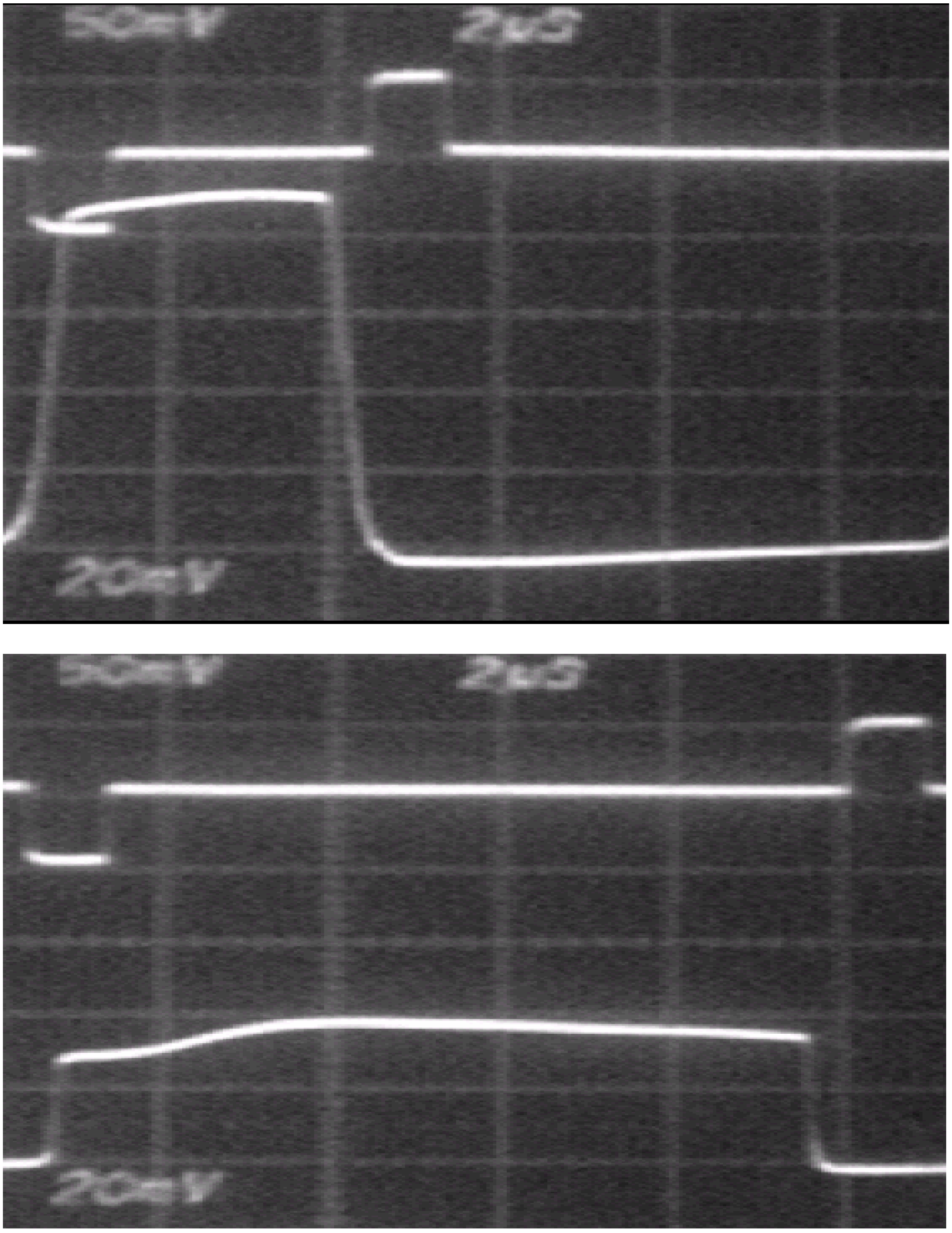

Figure AI-2: RF fanback (top trace) and WCM data (bottom trace) for momentum mining in the Recycler. Initial beam distribution (top picture) and the stretched beam distribution (bottom distribution). (2 μsec/division)

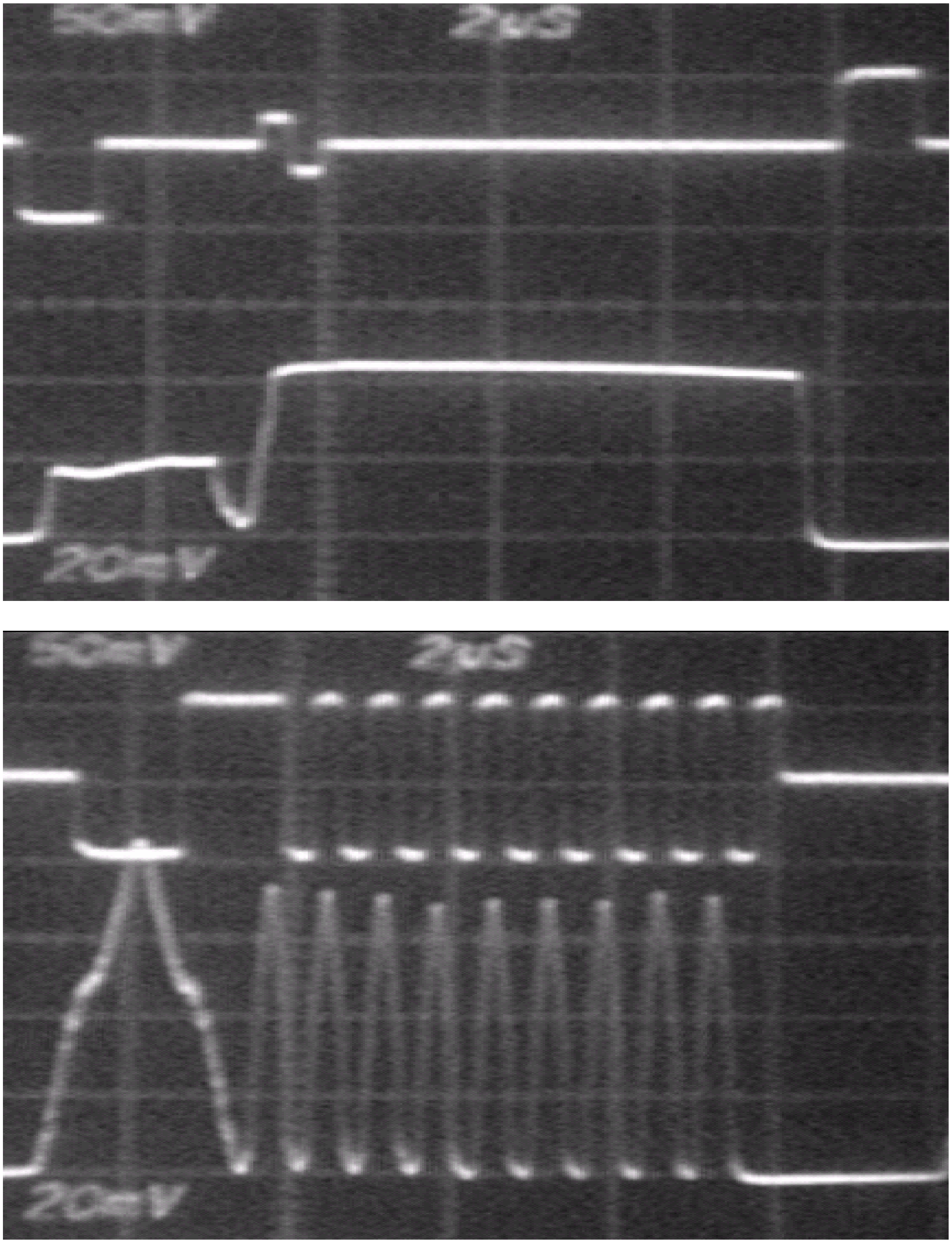

Figure AI-3: Same as figure A2. Top picture after mining. Bottom picture after capture in 6 eVs beam in 10.4eVs buckets.

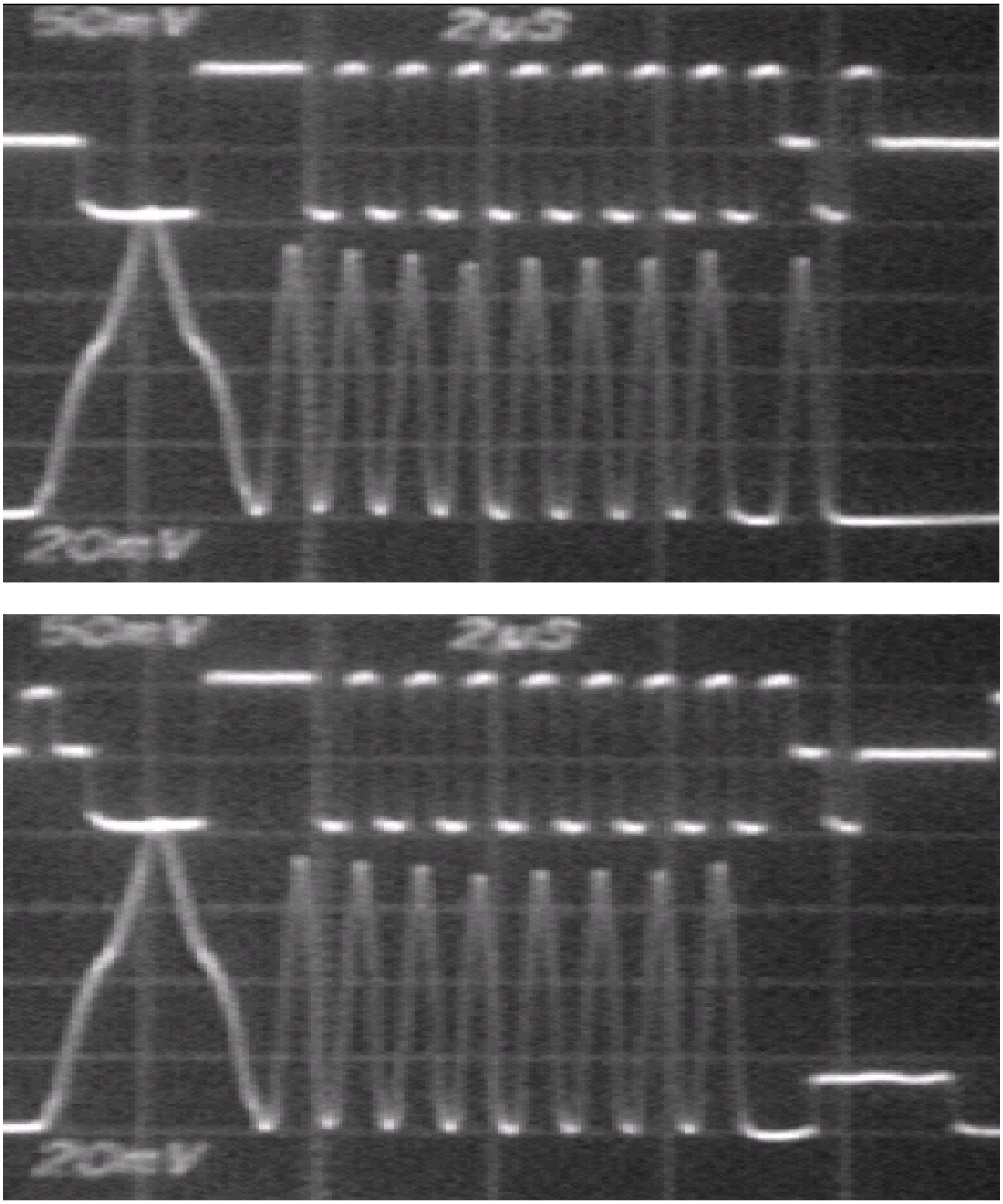

Figure AI-4: Same as figure A2. Top picture after bringing the ninth bunch to extraction region. Bottom picture after stretching the 9^{th} bunch by 1.59µsec.

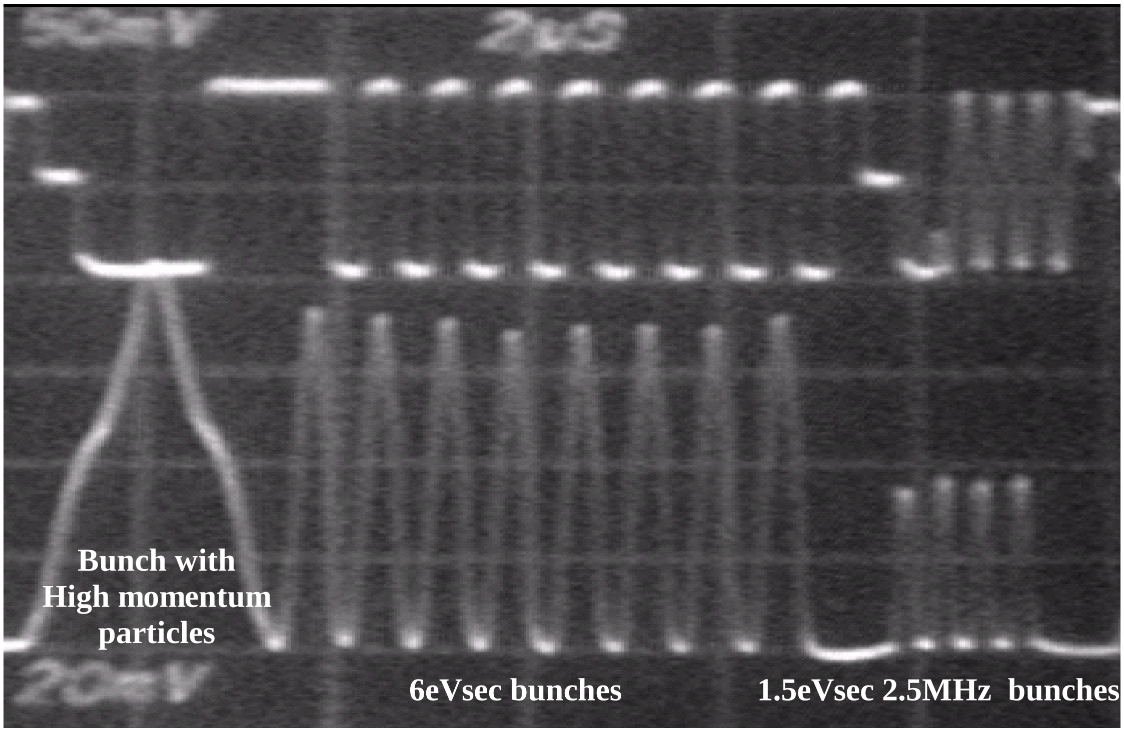

Figure AI-5: Final configuration for first pbar transfer to the Tevatron.

Pilot shots for studies:

With the present scheme in place we should be able to do a few pilot shots (low intensity pbar transfers through accelerator chain for tuning the accelerators) to MI. I suggest two viable methods.

1) Before momentum mining the pilot shots can be made from the stretched distribution using a method of extraction presently in place. or

2) One can pull-out the beam from the bucket with high momentum particles.

Both of these schemes need some compromise; we need to develop some extra rf modules as a part of the operation.

From these series of experiment I am convinced that with some improvements in the Recycler LLRF system we should be able to transfer equal intensity, equal emittance, low momentum pbar bunches to Tevatron collider operation without much emittance dilution even without electron cooling in place in the Recycle. With electron cooling this will be even better.